

18.06 Linear Algebra, Fall 2011

Recitation Transcript – Differential Equations and  $\exp(At)$

LINAN CHEN: Hi. Welcome back to recitation.

In the lecture, you've learned eigenvalues and eigenvectors of a matrix. One of the many important applications of them is solving a higher order linear differential equation with constant coefficients. A typical example is like what I've written on the board here.  $y$  is a function of  $p$ , and  $y$  and its derivatives satisfy this equation. As you can see, it involves  $y$ ,  $y'$ , and all the way to its third derivatives.

So our first goal is to solve this differential equation for its general solution using the method of matrix. So the very first thing that we should do is to find out which matrix we should be working with. So after that, we also want to say something about the explanation of this matrix  $A$ . We want to find out the first column of this matrix exponential.

Why don't you hit the pause now, and try to write down this matrix  $A$  by yourself. But before you continue, make sure you come back to this video and check with me you've got the correct  $A$ . I'll see you in a while.

OK, let's work together to transform this problem into linear algebra. The idea is to put  $y''$ ,  $y'$ , and  $y$  together as a vector. And let me call this vector  $u$ . So of course, vector  $u$  is also a function in  $t$ . So this is vector  $u$ . If this is  $u$ , what's going to be  $u'$ ? OK,  $u'$  is going to be, so I take derivative of every coordinate here that's going to be  $y'''$ ,  $y''$ , and  $y'$ .

So this is our  $u'$ . And my goal is to write  $u'$  as a matrix, call it  $A$  times vector  $u$  itself. So I want to put a matrix here. And I want to create this matrix by incorporating this differential equation. If you move everything, except  $y'''$  to the right-hand side of the equation, you can read  $y'''$  is equal to negative 2 times  $y''$ . So  $y'''$  is negative 2 times  $y''$  plus  $y'$ . That's plus 1 times  $y'$  plus  $2y$ . That's  $2y$ , right? That gives you the first row.

Then look at the second coordinate, this  $y''$ .  $y''$  is simply itself. So you rate  $y''$  is equal to 1,  $y''$  then 0 0. That's the second row. Well same thing happens to

the last row.  $y'$  is again itself. So that's  $0 \ 1 \ 0$ . That is our matrix  $A$ . Did you get the right answer?

So we have transformed this equation, this third order ordinary differential equation of  $y$  into a first order differential equation of  $u$ . Although  $u$  is a vector, but if we can solve this equation for  $u$ , we have all the information we need for  $y$ .

So let's plan on solving this equation. In order to solve this equation, we will need the eigenvalues and eigenvectors of this matrix  $A$ . Again, this is a good practice for you. Why don't you possibly do again, and try to complete this problem on your own. When you're ready, I'm going to come back and show you how I did it.

Let's finish up everything together. So as we said, we need the eigenvalues and eigenvectors of matrix  $A$ , and that involves computing the determinant of the following matrix. So I want to compute the determinant of  $A - \lambda I$ .

Let's write it out. That's the determinant of  $\begin{vmatrix} -2 - \lambda & 1 & 2 \\ 1 & -\lambda & 0 \\ 0 & 1 & -\lambda \end{vmatrix}$ . So we need the determinant of this three by three matrix. Do it in your favorite way. You can either use the big summation formula, or you can do by cofactor along any row or any column.

The correct answer should be this is equal to  $1 - \lambda + \lambda^2 + \lambda^3$ . And this polynomial has three roots.  $1$ ,  $-1$ , and  $-2$ . These are the eigenvalues we're looking for. So let me write it here.  $\lambda_1 = 1$ .  $\lambda_2 = -1$ . And  $\lambda_3 = -2$ .

So now what we need is the eigenvector corresponding to each eigenvalue. Let's take  $\lambda_1 = 1$  for example. The eigenvector of  $A$  corresponding to  $\lambda_1 = 1$  is in the null space of the matrix  $A - \lambda_1 I$ , so in this case it's  $A - I$ . So it's in the null space of this matrix. In other words, we are looking for a vector, let's call it  $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$ , a column vector  $a$ ,  $b$  and  $c$ , such that this matrix multiplying  $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$  gives me  $0$ . So if you write it out that's going to be  $A - I = \begin{bmatrix} -3 & 1 & 2 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix}$  times  $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$  is equal to  $0$ .

OK. Could we choose constants  $a$ ,  $b$ ,  $c$  such that this is always true? Well if you read the last row, so the last dot product, it says that  $b$  has to be equal to  $c$ . And if you read the second row it says that  $a$  has to

be equal to  $b$ . Which means  $a$  is equal to  $b$  is equal to  $c$ . And if this relation is true, the first product is always going to be 0. So that simply means we can choose the first eigenvector, the eigenvector corresponding to  $\lambda_1$ , to be  $x_1$  is equal to  $(1, 1, 1)^T$ . So we choose the first time eigenvector to be the column vector with all the coordinates being 1.

And you can do the same thing to  $\lambda_2$  and  $\lambda_3$ . But please allow me to skip the computation here. I'm going to write out the answer for you. So  $x_2$ , the eigenvector corresponding to the second eigenvalue is going to be equal to  $(1, -1, 1)^T$ . And  $x_3$  is going to be  $(4, -2, 1)^T$ .

Now we've got everything we need in order to create the general solutions for  $u$ . So we have eigenvalues, we have the corresponding eigenvectors. What should be  $u$ ? The general solution for  $u$  is equal to some constants,  $c_1$ , times  $e^{\lambda_1 t}$ . So in this case  $e^t$  times the first eigenvector,  $x_1$ . Plus some other constant  $c_2$  times  $e^{\lambda_2 t}$ .

So  $e^{-t}$  times  $x_2$ . That's the second eigenvector. Then plus some other constant,  $c_3$ , times  $e^{\lambda_3 t}$ . So  $e^{2t}$  times  $x_3$ . That gives you the general solution for  $u$ .

As we just said, if you know what  $u$  is, you have all the information you need for  $y$ . Just in case you're curious about what  $y$  is, you can just take the last coordinate of  $x_1$ ,  $x_2$ , and  $x_3$ . And you can see that all of them are 1. So  $y$  is simply equal to  $c_1 e^t + c_2 e^{-t} + c_3 e^{2t}$ . And the choice of  $c_1$ ,  $c_2$ , and  $c_3$  is completely arbitrary.

So that completes the first part of this question. In the second part, we want to say something about the exponential of  $A$ . So let me first give you the recipe to cook up the exponential of  $A$ . The exponential of  $A$  is equal to the product of three matrices. So you usually we denote them by  $S e^{\Lambda t} S^{-1}$ . And you may ask what  $S$  is, and what this matrix is.

So  $S$  is the matrix that has  $x_1$ ,  $x_2$ , and  $x_3$  being its column vectors. So  $S$  is  $(x_1, x_2, x_3)$ . Let me copy it down here. So that's  $(1, 1, 1, 1, -1, 1, 4, -2, 1)$ . And the matrix in the middle,  $e^{\Lambda t}$  is a diagonal matrix. So  $e^{\Lambda t}$  is a diagonal matrix, and its diagonal and trace are given by  $e^{\lambda_1 t}$ , so that's  $e^t$ , then  $e^{\lambda_2 t}$  negative  $t$ , and  $e^{\lambda_3 t}$  makes it  $2t$ . 0 everywhere else. So that's  $e^{\Lambda t}$ .

Then the exponential of this  $A$  is given by the product of these three matrices. It looks a bit complicated because it involves the inverse of  $S$ . But luckily, we only want the first column of the result. So if we consider this product, we can see the product of the first two matrices is relatively easy, because this is a diagonal matrix, and we know that  $S$  is given by these columns. So the result of the product of these two is simply multiplying the columns of  $S$  by these coefficients respectively.

So you expect to get  $e$  to the power  $\lambda t$ ,  $x_1$ , times  $e$  to the power-- sorry. The second column should be  $e$  to the power negative  $t$ ,  $x_2$ . The third column should be  $e$  to the power negative  $2t$ ,  $x_3$ .

And here, what we should put is  $S$  inverse. But we don't need everything from  $S$  inverse, because as we just said, we only need the first column of this result. And the first column of this product is going to be given by linear combinations of these columns, and the coefficients are going to be given by the first column  $S$  inverse. So our goal should be just to get the first column of  $S$  inverse.

Then what if the first column of  $S$  inverse? Well the formula for  $S$  inverse is  $S$  inverse is going to be the reciprocal of the determinant of  $S$ , so  $1$  over determinant of  $S$  times the transpose of a matrix  $C$ . This matrix  $C$ , the entries of this matrix  $C$  are given by cofactors of matrix  $S$ . And then you take transpose, you divide everything by the determinant of  $S$ . The result will be  $S$  inverse.

And we only need the first column of this matrix. Let's try to write the first column out. Well again, do it in your favorite way to compute the determinant of  $S$ . The result should be  $1$  over  $6$ . So the determinant of  $S$  is  $6$ .

Then what is the first column of  $C$  transpose? Well we can read it from here. This spot, the  $1, 1$  spot, should be the cofactor of this spot here. That make this  $1$ , minus negative  $2$ , which is  $1$ , so we put  $1$  here.

Now this spot will be the cofactor of this entry here. so that's  $1$  minus negative  $2$ , that's  $3$ . But this is  $12$  entry, so you should put a negative sign in the front. Then the last stop should be the cofactor of this entry here, which is  $1$  minus negative  $1$ , that's  $2$ . Something else here.

Two warnings. First, don't forget this transpose sign. Second, don't forget this negative sign.

We've got the first column of  $S$  inverse, and that's all we need. So we put it here. That's  $1/6$ ,  $-1/2$  and  $1/3$ . That's good enough for me. Now I can write up the first column of exponential of  $A$ .

So the first column of the exponential of  $A$ , I'm going to write it here. That's going to be equal to the linear combination of these columns. So that's  $1/6$  of the first column, that's  $e$  to the power  $t$  over  $6$  times  $x_1$ . Plus this times this, so that's going to be minus  $1/2$  of  $e$  to the power  $t$  times  $x_2$ . The plus  $1/3$  of  $e$  to the power  $t$  times  $x_3$ . That's the first column of the exponential  $A$ . And then with the other two columns.

That's the answer. If you want more practice, you can certainly complete this  $S$  inverse, and then you can also complete the exponential of  $A$ . But I will leave the rest to you.

OK, I hope this example shows you that linear algebra can be a powerful tool in solving higher order ordinary differential equations with constant coefficients. And we have demonstrated the standard procedure to do it, and we also practiced how to calculate the exponential of a matrix. Thanks for watching, and see you next time.

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